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13. ABSTRACT *(Maximum 200 words)*

This is the Final Report for ARO Contract DAAL-88-K-0063. The contract covers the period 4/1/88 to 3/31/91. Research carried out was in the area of simulation methodology and aimed at developing statistical methods for analyzing computer simulation output.

14. SUBJECT TERMS

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SIMULATION METHODOLOGY

by

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and
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1. INTRODUCTION

This contract covered the period April 1, 1988 to March 31, 1991. The participating scientific personnel included two faculty members and seven Ph.D. students. All of the students completed a Ph.D. in Operations Research, four also earned an M.S. in Operations Research, and two earned an M.S. in Statistics.

The main thrust of our research has been in developing new methods for analyzing the output from computer simulations. The technical work can be divided into three areas: simulation output analysis, variance reduction, stochastic optimization, and generalized semi-Markov processes. Below we mention some of the most important results in each area.

2. SIMULATION OUTPUT ANALYSIS

The initial bias problem arises in the context of estimating steady-state parameters of a system because initial conditions for the simulation are atypical of the steady-state. Technical Reports 26, 50, 51, 59, and 62 contain new methods and insights for handling initial bias. Technical Reports 50, 51 analyze the consequences of deleting an initial portion of the simulation, while Technical Report 62 develops a method for parallel simulation using non-linear regression. A new low-bias steady-state estimators for equilibrium processes is developed in [25]. Steady-state estimators, such as ratio estimators which arise in regenerative simulation, are normally-biased (although asymptotically unbiased). The idea in [25] is to estimate the first-order bias term from the simulation data and then subtract it from the classical estimator to obtain the low-bias estimate.

The use of parallel computing environments to carry out simulations is in its infancy. Technical Report 56 develops a procedure for carrying out such simulations under a completion time constraint.

Standardized time series is a new approach to the steady-state simulation problem that exploits the machinery of weak convergence of stochastic processes. In [19] we develop a mathematical framework for rigorously analyzing standardized time series. Extensions of standardized time series to a multivariate setting will be forthcoming in a subsequent technical report.

3. VARIANCE REDUCTION TECHNIQUES

Variance reduction techniques (VRT's) aim to increase the efficiency of computer simulation and thus lie at the core of simulation methodology. Importance sampling is a classical VRT in the setting of independent, identically distributed random variables. In [16] importance sampling is extended to cover stochastic simulations, in particular discrete and continuous Markov chains, semi-Markov processes, and generalized semi-Markov processes. Technical Reports 39, 53, and 65 apply importance sampling ideas for the simulation of rare events which arise in highly dependable systems. The idea here is to force the rare events to occur more frequently by using a "change of measure" in the simulation. Of course, to estimate the original probability of the rare event one needs to compensate for the change of measure and this involves using likelihood rations.

The problem of estimating the expected infinite-horizon discounted cost from running a stochastic system is studied in [15]. By exploiting stochastic structure estimators are constructed that exhibit smaller variances.

4. STOCHASTIC OPTIMIZATION VIA SIMULATION

Traditionally, it has been difficult to apply simulation in conjunction with optimization routines. A major problem has centered on the fact that naive simulation does a (very) poor job of estimating derivatives. Good derivative evaluations are, however, critical to most efficient optimization routines.

An active area of research in the last five years is developing efficient estimators for the gradient of the steady-state system performance as a function of system parameters. The two principal methods proposed are likelihood ration and perturbation analysis. Technical Reports 27, 32, 41, and 54 contain a thorough discussion of these methods plus new results on several aspects of this problem. Gradient estimation for highly dependable systems is developed in Technical Report 65.

Gradient estimates permit the simulator to use methods of stochastic approximation type to optimize the system under study. Technical Reports 31, 43, and 63 contain results on the use of stochastic approximation techniques for the optimization of systems.

5. GENERALIZED SEMI-MARKOV PROCESSES

Modeling complex stochastic systems which are non-Markovian is a difficult task. One of the most promising environments in which to carry out this modeling is generalized semi-Markov processes (GSMP's). GSMP's handle non-Markovian events by keeping track of the clock times until such events occur. In this sense GSMP's incorporate the old idea of supplementary variables. A GSMP formalism for modeling discrete-events systems is contained in [12]. Application of GSMP's to queueing systems is discussed in [6].

6. SCIENTIFIC PERSONNEL

The following scientific personnel were supported on this contract:

Faculty

Peter W. Glynn, Principal Investigator
Donald L. Iglehart, Principal Investigator

Students

Sigrún Andradóttir, earned M.S. in Statistics and Ph.D. in Operations Research.
James Calvin, earned Ph.D. in Operations Research.
Chia-Hon Chien, earned M.S. and Ph.D. in Operations Research.
David Muñoz, earned M.S. and Ph.D. in Operations Research.
Marvin Nakayama, earned M.S. and Ph.D. in Operations Research.
Scott D. Schulz, earned M.S. and Ph.D. in Operations Research.
Nayyar Shahabuddin, earned M.S. in Statistics and Ph.D. in Operations Research.

7. ARO TECHNICAL REPORTS

NUMBER	DATE	TITLE	AUTHORS
26	10/87	A New Initial Bias Deletion Rule	Peter W. Glynn Donald L. Iglehart
27	10/87	Likelihood Ratio Gradient Estimation: An Overview	Peter W. Glynn
28	04/88	Simulation Methods for Queues: An Overview	Peter W. Glynn Donald L. Iglehart
29	08/88	A Non-Rectangular Sampling Plan for Estimating Steady-State Means	Peter W. Glynn
30	09/88	A GSMP Formalism for Discrete-Event Systems	Peter W. Glynn
31	02/89	Stochastic Optimization by Simulation: Some Experiments with a Simple Steady-State Queue	Pierre L'Ecuyer Nataly Giroux Peter W. Glynn
32	02/89	A Unified View of Infinitesimal Perturbation Analysis and Likelihood Ratios	Pierre L'Ecuyer
33	03/89	Computational and Statistical Issues in Discrete-Event Simulation	Peter W. Glynn Donald L. Iglehart

34	05/89	Discrete-Time Conversion for Simulating Finite-Horizon Markov Processes	Bennett L. Fox Peter W. Glynn
35	06/89	Markov Chain Moment Formulas for Regenerative Simulation	James M. Calvin
36	06/89	Smoothed Limit Theorems for Equilibrium Processes	Peter W. Glynn Donald L. Iglehart
37	06/89	Small Sample Theory for Steady State Confidence Intervals	Chia-Hon Chien
38	07/89	Diffusion Approximations	Peter W. Glynn
39	07/89	A Unified Framework for Simulating Markovian Models of Highly Dependable Systems	Ambuj Goyal Perwez Shahabuddin Philip Heidelberger Victor F. Nicola Peter W. Glynn
40	08/89	Tightness of Synchronous Processes	Peter W. Glynn Karl Sigman
41	08/89	Likelihood Ratio Derivative Estimators for Stochastic Systems	Peter W. Glynn
42	08/89	Queues with Negative Arrivals	Erol Gelenbe Peter W. Glynn Karl Sigman
43	08/89	Optimization of Stochastic Systems Via Simulation	Peter W. Glynn
44	10/89	Uniform Limit Theorems for Synchronous Processes with Applications to Queues	Peter W. Glynn Karl Sigman
45	11/89	Jackknifing Under a Budget Constraint	Peter W. Glynn Philip Heidelberger
46	11/89	A Lyapunov Bound for Solutions of Poisson's Equation	Peter W. Glynn
47	11/89	The Asymptotic Efficiency of Simulation Estimators	Peter W. Glynn Ward Whitt
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49	12/89	The Covariance Function of a Regenerative Process	Peter W. Glynn
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51	12/89	Analysis of Initial Transient Deletion for Replicated Steady-State Simulations	Peter W. Glynn Philip Heidelberger
52	12/89	Poisson's Equation for the Recurrent M/G/1 Queue	Peter W. Glynn
53	01/90	Fast Simulation of Dependability Models with General Failure, Repair and Maintenance Processes	Victor F. Nicola Marvin K. Nakayama Philip Heidelberger Ambuj Goyal
54	01/90	Likelihood Ratio Sensitivity Analysis for Markovian Models of Highly Dependable Systems	Marvin K. Nakayama Ambuj Goyal Peter W. Glynn
55	01/90	The Asymptotic Validity of Sequential Stopping Rules for Stochastic Simulations	Peter W. Glynn Ward Whitt
56	02/90	Analysis of Parallel, Replicated Simulations Under a Completion Time Constraint	Peter W. Glynn Philip Heidelberger
57	03/90	Estimating the Asymptotic Variance with Batch Means	Peter W. Glynn Ward Whitt
58	04/90	Locating the Maximizer of a Random Function	James M. Calvin
59	05/90	Experiments with Initial Transient Deletion for Parallel, Replicated Steady-State Simulations	Peter W. Glynn
60	05/90	Departures from many Queues in Series	Peter W. Glynn Ward Whitt
61	07/90	Pathwise Convexity and its Relation to Convergence of Time-Average Derivatives	Peter W. Glynn
62	08/90	Bias Reducing, Steady-State Estimators for Parallel Simulation	Scott David Schulz
63	08/90	Stochastic Optimizations with Applications to Discrete Event Systems	Sigrún Andradóttir
64	09/90	Simulation and Analysis of Highly Reliable Systems	Perwez Shahabuddin
65	01/91	Simulation of Highly Reliable Markovian and non-Markovian Systems	Marvin K. Nakayama
66	02/91	Diffusion Approximations for Complex Repair Systems	Donald L. Iglehart Atam P. Lalchandani

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